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Dynamic Changes in Melbourne's Urban Vegetation Cover—2001 to 2016

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Abstract: Understanding changes in urban vegetation is essential for ensuring sustainable and healthy cities, mitigating disturbances due to climate change, sustaining urban biodiversity, and supporting human health and wellbeing. This study investigates and describes the distribution and dynamic changes in urban vegetation over a 15-year period in Greater Melbourne, Australia. The study investigates how vegetation cover across Melbourne has changed at five-yearly intervals from 2001 to 2016 using the newly proposed *dynamic change* approach that extends the net change approach to quantify the amount of vegetation gain as well as loss. We examine this question at two spatial resolutions: (1) at the municipal landscape scale to capture broadscale change regardless of land tenure; and (2) at the scale of designated public open spaces within the municipalities to investigate the extent to which the loss of vegetation has occurred on lands that are intended to provide public access to vegetated areas in the city. Vegetation was quantified at four different times (2001, 2006, 2011, 2016), using the normalized difference vegetation index (NDVI). Dynamic changes of gain and loss in urban vegetation between the three periods were quantified for six local government areas (LGAs) and their associated public open spaces using a change matrix. The results showed an overall net loss of 64.5 square kilometres of urban vegetation from 2001 to 2016 in six LGAs. When extrapolated to the Greater Melbourne Area, this is approximately equivalent to 109 times the size of Central Park in New York City.

Keywords: urban vegetation; normalized difference vegetation index (NDVI); dynamic change and spatio-temporal change

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1. Introduction

Urban greenspaces are of the utmost importance for cities due to their roles in improving health and wellbeing [1], ensuring a sustainable supply of ecosystem services [2,3], supporting biodiversity conservation [4–6], enhancing social cohesion [7] and adding to the aesthetics and beauty of the landscape [8]. Maintaining and enhancing adequate urban vegetation is also regarded as a key strategy to reduce the impact of urban heat islands in the context of rapid urbanisation [9]. Research in access to urban greenspace has shown that the most vulnerable communities have been disadvantaged in accessing nature in urban settings [10,11]. As a reflection of the importance of addressing this issue, the United Nations Sustainable Development Goals include target 11.7, which provides broad-level policy guidance to "Provide universal access to safe, inclusive and accessible, green and public spaces" by 2030 [12].

Urban vegetation consists of the plants present in a city, including trees, shrubs, grass and herbs [13]. Urban greenspaces are often conceptualised as different arrangements of vegetation cover and their associated land use features and affordances [14,15], such as parks, street trees, urban farms, urban forests, private gardens, botanical gardens, open spaces and sports ovals [16–19]. Urban greenspace has also been classified into formal and informal, in reference to management perspectives [20]. The broad term 'urban greenspace' can refer to over 100 different types of features and structures that support urban vegetation [17,21]. For the purpose of this paper, we focus on urban vegetation cover, regardless of the form, land-use or land tenure of the associated greenspace. Furthermore, while qualitative aspects of vegetation (e.g., vertical structure, plant species composition) are important for biodiversity responses, our study focuses solely on a quantitative assessment of vegetation cover.

The amount of vegetation in cities changes over space and time in response to various drivers, such as rapid urbanisation, ecological disturbances, changes in policies, political decisions and changes in socio-economic and demographic patterns [22–26]. Therefore, for it is important to track changes in vegetation cover to monitor the impact of these changes. However, few studies have empirically described changes in urban vegetation [27–31], and these existing studies have shown mixed results in different contexts. For instance, in assessing Landsat imagery of more than ten thousand cities, Corbane et al. [28] found that urban greenness has increased over the period of 1990 to 2014 for most of the world's urban centres, including 32 mega cities. In contrast, Richards and Belcher [27], using a supervised remote sensing framework with Landsat images obtained between 2000 and 2015, found that urban vegetation has declined in most urban locations greater than 15 square kilometers globally and also reported that most of the loss is happening in the Southern Hemisphere. Using high-resolution images, in contrast to Corbane et al. [28] and Richards and Belcher [27], Zhou et al. [29] found significant changes in urban greenspace in nine major cities of China, which had been previously found to have little or no change in urban greenspace using moderate resolution imageries.

Most studies have assessed the overall or net change in greenspace or vegetation cover, which provides a single measure of how much change has happened. While net change is a valuable metric, it is not always easy for related stakeholders to process and implement it in decision making, as it does not provide information about how much of the change is due to gains or losses [30,32,33]. Furthermore, net change can be misleading; for example, large gains and losses in urban vegetation within the landscape in different places may result in no net change overall, despite substantial dynamics within the landscape. More nuanced metrics, such as the dynamic change approach employed by Wang et al. [30], may offer additional information that can be used to develop more sophisticated approaches to policy and practice. The dynamic change approach provides a comprehensive and broad view of change. Unlike the traditional net change approach, it provides information on both gain and loss simultaneously. It also shows how the change is happening, that is, the quantity of change from one category of land cover to another.

It is important to understand patterns in long-term change in urban vegetation because this will impact the flow of ecosystem services and ultimately affect the quality of the urban environment and the health of the population. For example, loss of urban vegetation cover has been linked to changes in peak stream flow, total discharge and sediment load [34], as well as stronger urban heat island effects [35]. Similarly, understanding the stability and dynamics of vegetation will support the decision making of related stakeholders (e.g., state government and local councils) to ensure an adequate distribution of greenspace for a sustainable supply of ecosystem services and biodiversity conservation. However, there have been few long term studies regarding urban vegetation change in cities, with most studies having been conducted over a short period of time [36,37].

In our study, we use the newly proposed *dynamic change* approach [30] to investigate how vegetation cover across Melbourne, Australia, has changed at five-yearly intervals from 2001 to 2016, enhancing our understanding of how vegetation has changed across the city over a 15-year time period. We examine this question at two spatial resolutions: (1) at the municipal landscape scale to capture broad-scale change regardless of land tenure; and (2) at the finer-scale of designated public open spaces within the municipalities to investigate the extent to which the loss of vegetation has occurred on lands that are intended to provide public access to vegetated areas in the city.

2. Material and Methods

2.1. Study Area

This study focused on the Greater Melbourne area, which includes 32 local government areas (LGAs). Melbourne's population has grown from around 3.3 million in 2001 to 4.5 million in 2016 and is currently projected to surpass Sydney to become the most populous city of Australia in the next couple of decades [38]. The greater Melbourne metropolitan area is approximately 1900 square kilometres and spans five distinct bioregions. These include the Victorian Volcanic Plains in the west, typified by basalt soils and cracking clays that historically supported grasslands and grassy woodland communities; the Gippsland Plains in the southeast, with heathlands and heathy woodlands on sandy aeolian soils; and the Highlands–Southern Fall region in the northeast parts of Melbourne, which supports denser woodlands and forests on more soils [39,40].

Melbourne has a temperate climate, with mean summer temperatures around 25 °C and mean winter temperatures around 13 °C. There is a strong rainfall gradient across the city, with an average ranging from 550 mm per annum in the west to 1200 mm per annum in the east [41]. During the 15-year period examined in this study, the Melbourne area has experienced climate-related disturbances in the form of drought conditions between 2001 to 2009, followed by higher-than-average rainfall in 2010 and 2011 [41], and two heat waves with the temperature above 40 degrees for three consecutive days in 2009 and 2014 [42].

Melbourne provides an interesting case study to test the dynamic change approach, as it has been the subject of previous studies of land cover change, but often over short time periods, or using the net change approach. Therefore, it is possible to compare the trends observed in our study with those previously reported in the literature using alternative methodologies to quantify change.

2.2. Data

LGA spatial boundaries were sourced from the State of Victoria's Spatial Datamart. Vegetation was estimated using the normalised difference vegetation index (NDVI) because it provides a robust estimate of vegetation presence or removal [43]. NDVI is calculated as the ratio of near-infrared (*NIR*, wavelength 0.77–0.90 μm) and red (*R*, wavelength 0.63–0.69 μm) bands of Landsat imagery, using the following Equation (1).

$$NDVI = \frac{NIR - R}{NIR + R} \tag{1}$$

We used a custom script [44] in Google Earth Engine to calculate the median NDVI value for each time period from the Landsat 7 satellite image collection (Top of Atmosphere, Tier 1). The custom script extracted all cloud-free pixels for the study area and period and identified the median NDVI value per pixel during a 12-month period either side of the year of interest. The median NDVI was calculated for four different times, as shown in Table 1.

Table 1. Time periods investigated during this study.

Year	Date Range Used to Calculate Median NDVI	Temporal Change
2001	1 July 2000–30 June 2002	T1 (2001–2006) T2 (2006–2011) T3 (2011–2016)
2006	1 July 2005–30 June 2007	
2011	1 July 2010–30 June 2012	
2016	1 January 2015–December 2016	

Median NDVI images for the study area and each study period were downloaded from Google Earth Engine and exported to QGIS for further analysis. Landsat 7 was used because it provides a medium resolution, appropriate for identifying broadscale differences in urban areas, and covers the entire study period, thereby reducing the error of comparing

NDVI values calculated from alternative imaging platforms (e.g., Landsat 5). By using the custom script that drew upon images for a 2-year time period, we were able to overcome the scan line corrector (SLC) failure that occurs in Landsat 7, as the data for the affected pixels were simply calculated from scenes in the overlapping path.

In this study, we used Landsat 7 images, which are among the most widely used satellite images for land use and greenspace change studies globally due to the frequency of images captured (twice a month) and their cost-effectiveness (being freely available). However, Landsat 7 has a spatial resolution of 30 m in the red (Band 3) and near-infrared (Band 4) regions, which means that in urban areas a pixel will often represent a mixture of vegetated and non-vegetated land covers. Therefore, although the 30-m resolution limits the ability of the study to capture finer-scale incremental gains and losses which would have been captured by high-resolution satellite images [45], we have deliberately included a mixed pixel class into our classification, as described in the next section, to partially capture these smaller changes in NDVI.

2.3. Reclassification Threshold and Accuracy

The land cover within the study area was classified into three categories: vegetated (V), non-vegetated (NV) and partially vegetated (PV). Vegetated (V) includes pixels in which vegetation is the dominant land cover. Non-vegetated (NV) includes all of the pixels in which the majority of the land cover is not vegetation (e.g., waterbodies, built structures, bare land and impervious surfaces). Partially vegetated (PV) is a category that captures pixels with a mix of vegetation and other land covers. Although the distinction between vegetated and non-vegetated pixels can be achieved relatively easily in some landscapes (e.g., agriculture or natural areas); urban areas often contain a highly heterogeneous mix of land covers at a fine scale, such as fragmented greenspaces, landscapes with scattered vegetation or vegetation within residential areas. The inclusion of partially vegetated (PV) categories allows an understanding of how vegetated (V) and non-vegetated (NV) areas have been changing in addition to the more prevalent heterogenous vegetation cover (PV) and more clearly illustrates the type of change that happens, which ultimately results in loss or gain in an urban setting.

To the best of our knowledge, this is the first study to include the category of partially vegetated (PV) in a classification of urban vegetation change. The inclusion of this category allowed us to distinguish between absolute change, instances where we were confident that there had been a gain or loss of vegetation because the pixel had changed from vegetated to non-vegetated or vice versa; compared to potential change, where some of the change may have been be due to factors such as variation in NDVI due to higher or lower rainfall; or uncertainty in the classification due to the difficulties of setting threshold NDVI values that work consistently across time and space.

The classification was applied based on NDVI thresholds. Although the use of NDVI threshold values to distinguish vegetated from non-vegetated land cover is regularly used in the scientific literature [46], a single threshold did not provide a satisfactory classification of vegetation cover across Greater Melbourne due to differences in topographic, climatic and geological factors present in the area. Therefore, separate thresholds were identified for each of the six metro partnership regions by manually adjusting the NDVI threshold for each partnership region in each time period, and then assessing the accuracy by quantifying the proportion of correctly classified land cover at 100 random points based on the visual interpretation of land cover for that time period in Google Earth. We achieved a classification accuracy of >80% for all time periods and partnership region combinations (Table 2). This approach of using customized NDVI thresholds may prove valuable for other researchers when working in cities that have steep rainfall gradients or diverse bioregions, as is the case for the Greater Melbourne area.

Table 2. NDVI thresholds for image classification into three categories (vegetated (V), non-vegetated (NV) and partially vegetated (PV) and their accuracy for six metro partnership regions (MPRs).

Metro Partnership Regions	NDVI Threshold Value			Accuracy (Percent)			
	Non-Vegetated (NV)	Partially Vegetated (PV)	Vegetated (G)	2001	2006	2011	2016
Eastern	<0.38	0.38–0.45	>0.45	89.27	86.30	85.84	81.51
Inner	<0.20	0.20–0.25	>0.25	86.85	89.64	86.45	86.06
Inner South East	<0.30	0.30–0.38	>0.38	90.17	89.13	89.37	84.54
Northern	<0.30	0.30–0.35	>0.35	95.99	92.90	95.17	93.62
Southern	<0.30	0.30–0.40	>0.40	93.10	88.51	93.68	93.10
Western	<0.25	0.25 0.32	>0.32	95.07	90.14	97.89	93.96

2.4. Change Calculation and Statistical Test

Change in vegetation was calculated over three five-year time periods (T1–T3) using a 3 × 3 change matrix. Gain and loss of vegetation were calculated based on the change in pixels from one category to another (see Figure 1). For example, a gain was recorded if non-vegetated (NV) pixels changed to partially vegetated (PV) or vegetated (V) pixels, and if partially vegetated (PV) pixels changed to vegetated (V) pixels, between two time periods. A loss was recorded if vegetated (V) pixels changed to non-vegetated (NV) or partially vegetated (PV) pixels, or partially vegetated (PV) pixels changed to non-vegetated (NV) pixels.

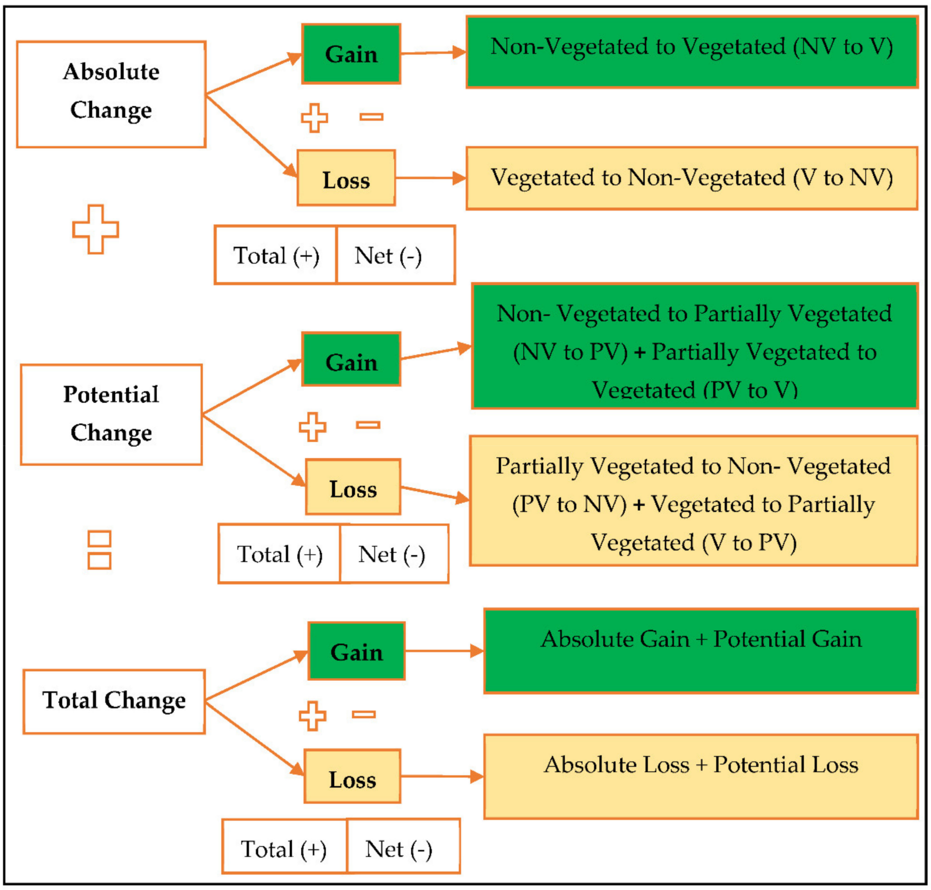


Figure 1. Diagram showing three types of changes—absolute, potential and total change. The diagram also explains how total and net changes within the three types of changes were calculated.

Changes observed within this study were categorized into three different categories (Figure 1):

- **Absolute change** is the change occurring between the vegetated (V) and non-vegetated (NV) categories. It involves two main processes: gain from non-vegetated to vegetated (NV to V) and loss from vegetated to non-vegetated (V to NV).
- **Potential change** involves four processes of change: (a) gain from partially vegetated to vegetated (PV to V), (b) gain from non-vegetated to partially vegetated (NV to PV), (c) loss from vegetated to partially vegetated (V to PV), and (d) loss from partially vegetated to non-vegetated (PV to NV).
- **Overall change** is the change that occurred as the sum of all six processes of change (Figure 1).

Each of the three categories of changes is summarised as total change or net change. The total change involves the sum of gains and losses in each process of change. The net change involves the difference between gains and losses of all six processes of change.

One-way repeated ANOVA was used to test the significance of all categories of changes within the three time periods (T1, T2 and T3) and study sites within Greater Melbourne.

Geospatial analyses were conducted in QGIS [47] and statistical analyses were conducted in the open access software package R [48].

To answer the first question, regarding how total vegetation has changed in Melbourne, six LGAs were selected using stratified random sampling within each metro partnership region (MPR) to ensure representation of both urbanized and urbanizing LGAs (Figure 2). These sample LGAs covered around 20 per cent of Greater Melbourne. Of the six LGAs, Melbourne, Hobsons Bay, Bayside and Whitehorse were urbanised before 2001 [49]. Hume and Mornington Peninsula were the least urbanised regions during 2001; however, large parts of these LGAs were urbanised in the period leading up to 2016.

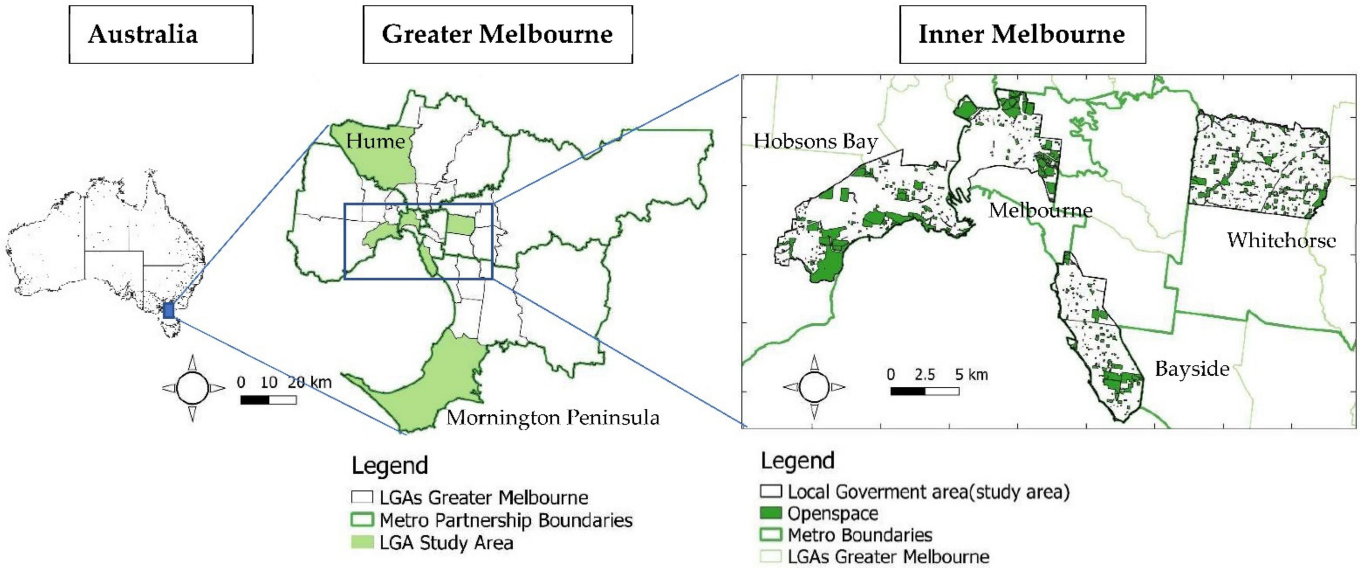


Figure 2. Study area showing Greater Melbourne with six local government areas (middle) and open space in four LGAs in Inner Melbourne (right). The location of Melbourne within Australia is shown in the left panel.

Public open space was defined using the Australian Research Centre for Urban Ecology (ARCUE) 2002 Public Open Space dataset. The open space boundaries included parks, botanical gardens and sports ovals, and excluded private gardens, farms and urban agriculture. Change in vegetation within open space features (question 2) were calculated for only the four LGAs which were fully urbanised before 2001 (Whitehorse, Melbourne, Hobsons Bay and Bayside), and therefore had a full coverage of features in the 2002 Public Open Space dataset.

3. Results

3.1. Municipality (LGA)-Level Change in Urban Vegetation Cover

Most of the absolute change from non-vegetated (NV) to vegetated (V) and vice versa, for the 2001–2006 (T1) and 2011–2016 (T3) time periods was in the form of the loss of vegetation cover, with all councils experiencing a loss of 0.3% (Mornington Peninsula in T3) to 4.4% (Hume in T1). The largest increase in vegetation cover was observed in the 2006–2011 (T2) time period with Melbourne, Hobson's Bay and Hume all recording an absolute gain of 1–2%. The trend across all three time periods, and for all six LGAs, displayed a loss-gain-loss trend (Figure 3; Supplementary Tables S1, S3 and S5).

There were slightly different patterns when the potential change to and from partially vegetated (PV) was included in the analysis. For example, the overall dynamic change increased from an average of 2% absolute change to an average of 17% when the potential change was included. However, the pattern of loss-gain-loss is consistent in T1-T2-T3 with or without the inclusion of potential change. All the LGAs experienced losses, with four LGAs experiencing 11% to 15% loss in T1. However, five LGAs achieved 2% to 10% gains in vegetation cover during T2, with the exception being Bayside. All the LGAs incurred losses in vegetation at T3 to an even greater extent than T1 (Figure 3). Four among the six LGAs recorded net losses between 13% and 22%.

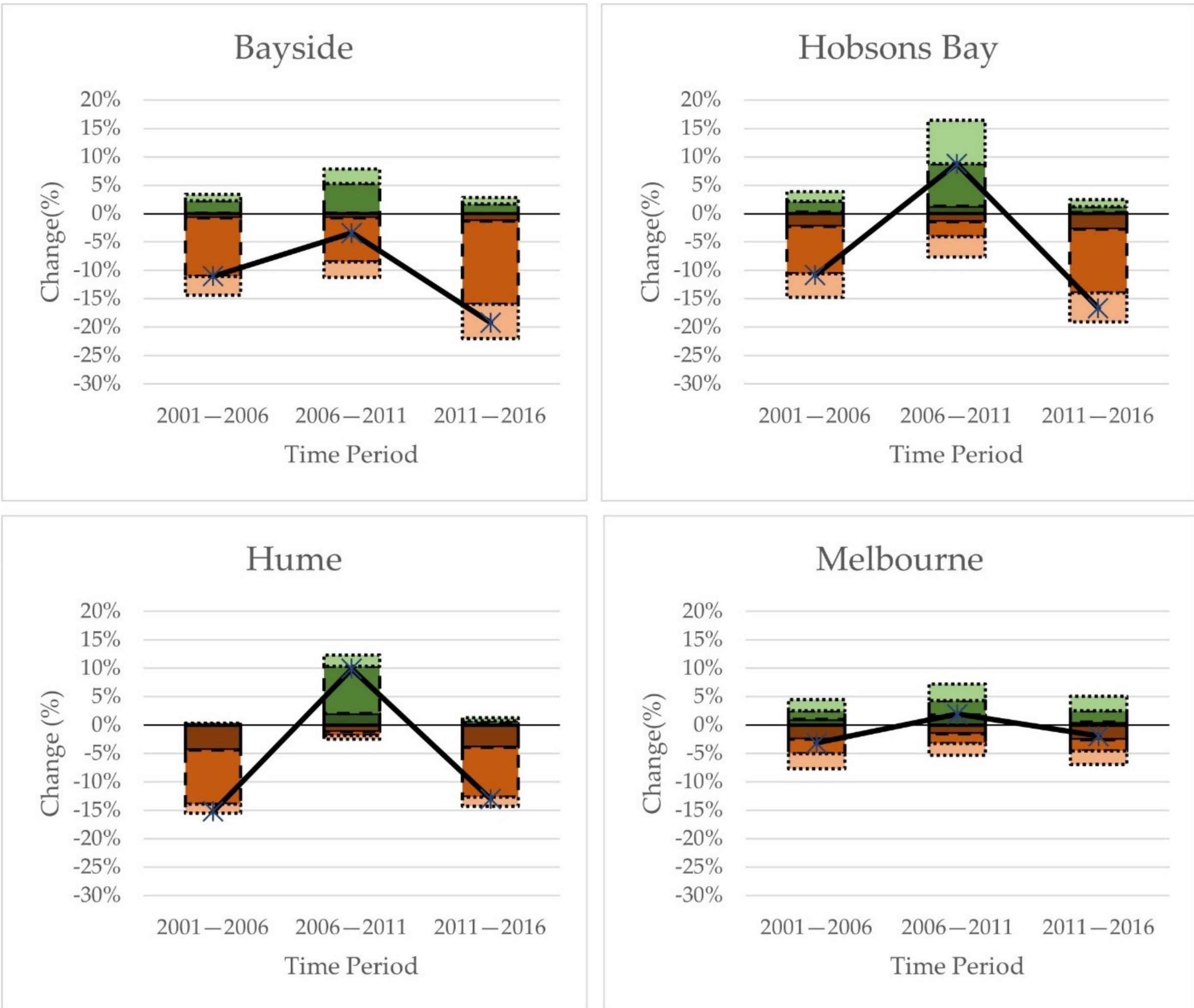
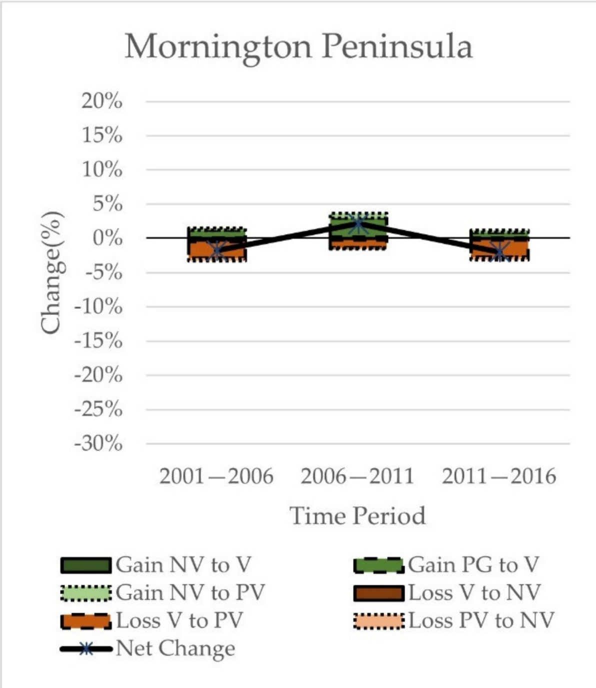


Figure 3. *Cont.*



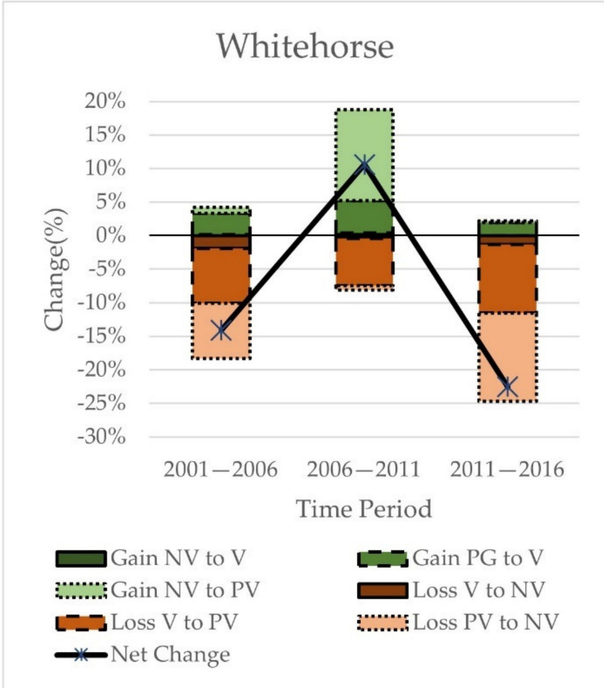


Figure 3. Pattern of change in urban vegetation over 15 years. The change has been shown over three time periods—T1 (2001 to 2006), T2 (2006 to 2011) and T3 (2011 to 2016). Net change and six processes of change have been included in the study, including: (1) gain from non-vegetated to vegetated (Gain NV to V), (2) gain from partially vegetated to vegetated (Gain PV to V), (3) gain from non-vegetated to partially vegetated (NV to PV), (4) loss from vegetated to non-vegetated (Loss V to NV), (5) loss vegetated to partially vegetated (Loss V to PV) and (6) loss from partially vegetated to non-vegetated (PV to NV). Among these six processes of changes, the gain (1) and losses (4) involving changes between non-vegetated (NG) and vegetated (G) pixels are referred to as absolute changes, whereas the other four processes (2, 3, 5, 6) are referred as potential changes.

In terms of the long-term absolute change in vegetation between 2001 and 2016, it was found that all the LGAs had experienced a loss of 0.5–7.5% in vegetation cover over the fifteen years (Table 3). The absolute gain was very low in comparison to the absolute loss in the vegetation. The greatest absolute changes were recorded in Hume (4787 Ha; 7.5%), followed by Mornington Peninsula (479 Ha; 0.7%) and Hobson’s Bay (461 Ha; 4.7%), whereas the lowest absolute change was observed in Mornington Peninsula and Bayside over the full study period (Table 3).

Table 3. Absolute change and net change in urban vegetation between 2001 and 2016 in six LGAs.

Local Government Areas (LGA)	Gross Gain 2001–2016 (Ha)	Gross Loss 2001–2016 (Ha)	Net Change 2001–2016 (Ha)	Net Change 2001–2016 (Percent)	Cumulative Change 2001–2016 (Percent)
Bayside	3.69	204.21	−200.52	−4.27%	−2.70%
Hobsons Bay	69.21	530.28	−461.07	−5.67%	−4.72%
Hume	197.01	4984.2	−4787.19	−7.52%	−7.16%
Melbourne	103.95	269.64	−165.69	−3.61%	−3.26%
Mornington Peninsula	218.88	697.68	−478.8	−0.52%	−0.73%
Whitehorse	27.72	405.45	−377.73	−4.63%	−3.18%

Potential changes appear as a more distinct process of change than absolute change in terms of quantity (Figure 3). Similar to the patterns observed for absolute change, the average potential loss of vegetation over 15 years (4.7%) was generally greater than the average potential gain in vegetation (2.5%).

3.2. Changes in Vegetation within Public Open Spaces

When we examined dynamic change within designated public open space areas, a similar trend of loss-gain-loss was observed across the three time periods (See Supplementary Tables S2, S4 and S6). The proportion of dynamic change observed in public open space features was almost half that at the LGA level (average of 8.3% compared to 16.64%, respectively) over the whole study period. The mean overall loss of vegetation was highest in the most recent T3 period (6.54%) in comparison to other two time periods (4.8% and 3.6% for T1 and T3 respectively), largely due to the contribution of potential losses from vegetated to partially vegetated (V to PV). Three out of four LGAs experienced an average loss of 7.7%, which was the highest loss of vegetation in a public open space during the final five-year period (T3). The largest dynamic changes were observed in Whitehorse and Hobsons Bay. In contrast, Bayside experienced the smallest dynamic change. The dynamic change of vegetation within public open spaces showed a three- to ten-fold increase when the potential change to and from partially vegetated (PV) was included (Figure 4), although the overall net change between years remained similar. For both absolute and potential change, the magnitude of the vegetation loss was higher than that of the gain in vegetation.

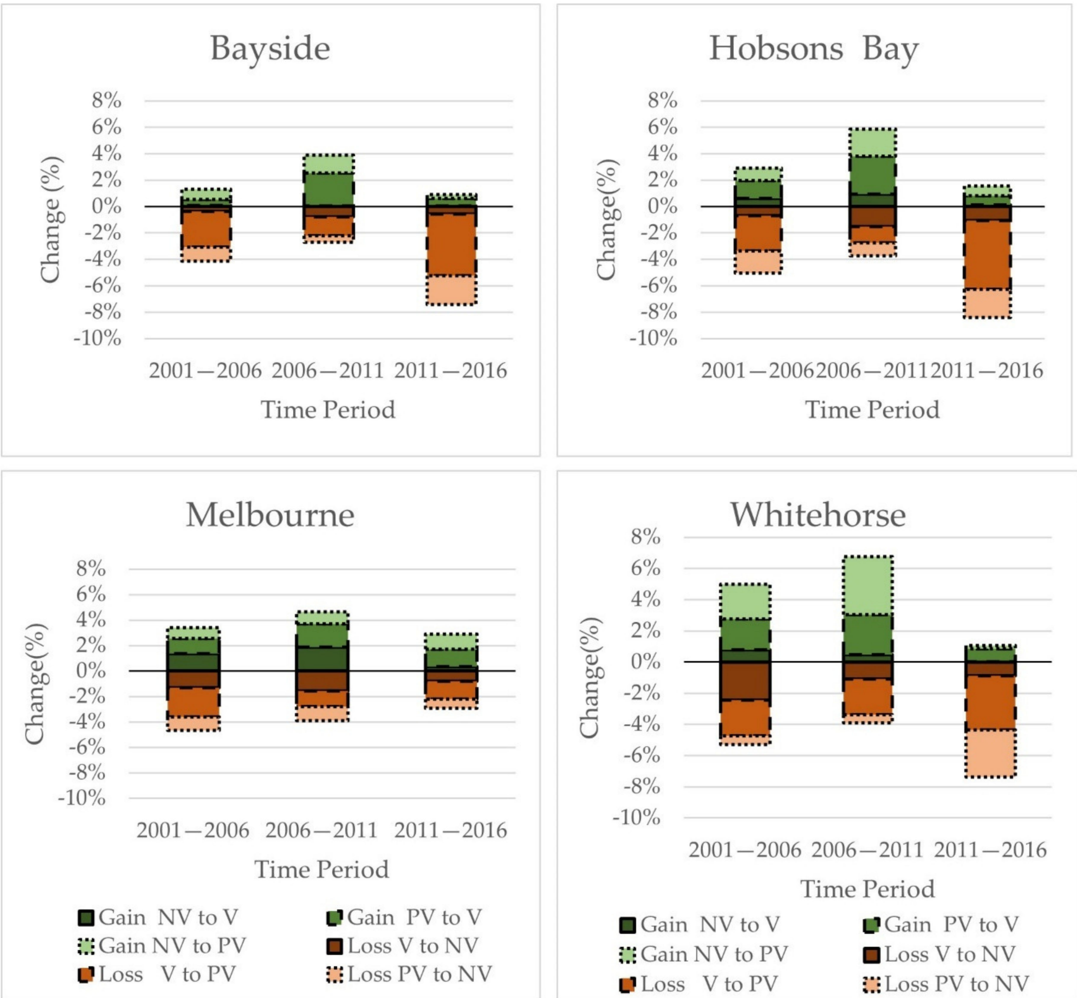


Figure 4. Pattern of change of vegetation within public open space features over a fifteen-year period. The change was calculated for three periods: T1 (2001 to 2006), T2 (2006 to 2011) and T3 (2011 to 2016). Six processes of change were included in the study: (1) gain from non-vegetated to vegetated (Gain NV to V), (2) gain from partially vegetated to vegetated (Gain PV to V), (3) gain from non-vegetated to partially vegetated (NV to PV), (4) loss from vegetated to non-vegetated (Loss V to NV), (5) loss from vegetated to partially vegetated (Loss V to PV) and (6) loss from partially vegetated to non-vegetated (PV to NV). Among six processes of changes, the gain (1) and losses (4) involving changes between non-vegetated (NV) and vegetated (V) pixels are referred to as absolute changes, whereas the other four processes (2, 3, 5, 6) are referred as potential changes.

The dynamic change in vegetation within public open spaces showed a three- to ten-fold increase when the potential change to and from partially vegetated (PV) was included (Figure 4), although the overall net change between years remained similar. For both absolute and potential change, the magnitude of the vegetation loss was higher than that of the gain in vegetation.

3.3. Testing the Statistical Significance of Change in Vegetation at the LGA Level

The one-way repeated ANOVA on all six types of change (Table 4) showed that net absolute, potential and overall changes were significantly different between the three time periods, whereas the total absolute, potential and overall changes were significantly different between LGAs.

Table 4. One-way repeated ANOVA test of different changes in vegetation with two factors for (1) time period and (2) site. * significant to 0.10; ** significant to 0.05; *** significant to 0.01. *p*-values shown for LGA scale models (Section 3.3) and changes within public open space (Section 3.4).

Change	Description	Factor	*p*-Value (LGA)	*p*-Value (Open Space)
Total absolute change	Gain (non-vegetated to vegetated) + loss (vegetated to non-vegetated)	Time Period	0.169	0.176
		Site	2.53×10^{-6} ***	0.135
Net absolute change	Gain (non-vegetated to vegetated)—loss (vegetated to non-vegetated)	Time Period	0.016 *	0.625
		Site	0.275	0.146
Total dynamic change	Sum of all gains and losses (six processes)	Time Period	0.169	0.655
		Site	2.38×10^{-6} ***	0.116
Net change	All gains − All losses	Time Period	0.002 **	
		Site	0.374	
Total potential change	Gain in potential vegetation ((partially vegetated to vegetated) + (non-vegetated to partially vegetated)) + loss in potential vegetation ((vegetated to partially vegetated) + (partially vegetated to non-vegetated))	Time Period	0.103	0.331
		Site	1.65×10^{-6} ***	0.050 *
Net potential change	Gain in potential vegetation ((partially vegetated to vegetated) + (non-vegetated to partially vegetated))—loss in potential vegetation ((vegetated to partially vegetated) + (partially vegetated to non-vegetated))	Time period (Significant)	0.003 **	0.025 *
		Site (Non-significant)	0.342	0.642

3.4. Testing the Statistical Significance of Change in Urban Vegetation within Public Open Space

The absolute changes and total dynamic changes were not significant for either the LGA or the time period, although there were detectable differences when potential changes were included (Table 4). The net potential change was significantly different between time periods.

4. Discussion

4.1. The Pattern of Change in Urban Vegetation between 2001 and 2016

Absolute and potential change in vegetation for LGAs and public open spaces both consistently showed a pattern of loss (2001–2006; T1), followed by a gain in 2006–2011 (T2), followed by a larger loss in 2011–2016 (T3). This loss-gain-loss pattern is likely to be due to climatic effects in T1 and T2, followed by accelerated urban development in T3. The reduction of vegetation from 2001 to 2006 (T1) coincided with a period of extended drought which broke in the year 2010 and was followed by above-average rainfall in 2010 and 2011 [50]. Although some of the loss of vegetation from 2001–2006 (T1) is likely to be due to urban development, the effect would be partially masked by the generally lower NDVI values that accompany periods of lower rainfall. Indeed, May et al. [51] also reported a significant loss of urban vegetation due to drought in Melbourne in that time period.

As more water was available to support active plant growth for the 2011 images, some of the mixed pixels will have a higher NDVI value even if the amount of vegetation present has not changed, it is simply growing more vigorously. This may lead to a higher number of pixels being classified as vegetated or partially vegetated, therefore painting a picture of increased vegetation during the 2006–2011 (T2) time period. This is where the dynamic change approach becomes valuable, as the loss of vegetation that was recorded during this time period tells a fuller story than can be gained when the focus is on the overall net change.

The average rainfall during the 2011–2016 period (T3) was more consistent; therefore, the absolute loss is likely to be largely explained by changes in the extent of vegetation cover over this time. Although the patterns of rainfall during this time period have a visible signature in the dynamic change patterns of vegetation over time, they do not explain all of the observed trends. For example, the LGAs and public open spaces still recorded losses of vegetation during T2 (2006–2011) (Figures 3 and 4). It is likely that the full extent of loss is partially obscured by the effect of rainfall and the implications for NDVI.

Although this study is the first in Australia to examine change in vegetation cover for Melbourne over an extended time period, there have been a number of studies that examined change over more recent time periods and recorded similar results. For example, Amati et al. [36] recorded an increase in hard surface from 34.25% to 37.26% in Melbourne between 2009 and 2016. This increase in impervious surface is due to both greenfield developments as well as infill and redevelopment, with 70% of annual construction allocated to the latter [52–54].

Several studies in Melbourne have identified several causes for the loss of urban vegetation canopy. Stanford and Bush [55] argue that rapid infill development is the major reason for the loss of urban vegetation cover. They also argue that fewer trees are being planted in the small space remaining after the private greenspace has been used for building bigger houses or additional houses. Indeed, although houses in Australian suburbs used to occupy around 30% of the total plot, they now occupy closer to 65% [53]. Heavy pruning of tree canopies near power lines in response to lessons from the catastrophic bushfires in 2009 in outer Melbourne have contributed to a further loss of urban vegetation [56,57]. Brunner and Cozens [58] have reported that providing vehicular access and increasing the sunlight in private urban dwellings have also contributed to canopy and vegetation loss.

There have been notable efforts by local and state government, land management agencies and other organisations to protect and enhance vegetation in Greater Melbourne. These include *Greening the West* [59], *City of Melbourne Urban Forest Strategy 2012–2032* [60], *Living Links* [61], *Mornington Peninsula Landcare Bio-Links* [62] and *Gardens for Wildlife* [63]. Although some of these positive measures were active during the study period investigated here, they were still not enough to fully counter the loss in parts of the landscape. Although only time will tell if ambitious canopy targets such as those set out in *Living Melbourne: Our Metropolitan Urban Forest* [63] will be met in the future, this research clearly highlights that the loss of vegetation is a clear and ongoing trend that will need to be addressed.

4.2. Heterogeneity and Homogeneity in the Change of Urban Vegetation

The net absolute change and net potential change displayed statistically significant differences between time periods. However, the total absolute change (the sum of both absolute gain and absolute loss) was statistically different between LGAs, revealing that absolute change is unevenly distributed across Greater Melbourne. In our study, four LGAs experienced three to four times as much change as that recorded for Mornington Peninsula or the City of Melbourne (Figure 3). For the LGA with the largest change in vegetation (Hume), the change was largely related to greenfield developments on the outer edge of the metropolitan area, whereas for the other LGAs, the majority of the change is likely to be associated with infill development, where residential blocks are subdivided and the garden areas are converted to new houses. This highlights the importance of strong planning protections, such as those applied in the two LGAs with the least change in vegetation. For example, the City of Melbourne is already highly urbanized and has been working to retain and enhance vegetation cover for over a decade, as demonstrated by their globally recognized Urban Forest Strategy, published in 2012. The Shire of Mornington Peninsula is part of a UNESCO Biosphere Reserve established in 2002 and has very few of the Urban Growth Areas that were established by the State of Victoria to guide residential development for the Greater Melbourne area.

Relatively little change in vegetation cover was recorded for the areas of public open space that were present in 2002. This suggests that the majority of the change in vegetation cover occurred elsewhere in the landscape. This result is consistent with those of Hurley et al. [37], who also found very small or no change in urban greenspace a the open-space level. However, the small changes that were recorded highlight that even public open spaces are still vulnerable to the loss of vegetation, and this incremental loss potentially has a more significant implication for reducing the benefits of larger consolidated areas of vegetation cover for biodiversity and urban cooling [64–67].

4.3. The Overall Change in Urban Greenspace in Greater Melbourne

The six LGAs, representative of the range of LGAs present within the Greater Melbourne Area, all recorded a net loss in greenspace over a 15-year period. To compensate for the effect of extreme weather events, such as drought during the early to mid-2000s, the heat waves of 2008 and the higher-than-average precipitation during 2010 and 2011, the long term absolute change was analysed using 2001 and 2016 data directly [68]. Due to this difference in the years being compared, there is a small difference in the result between long-term absolute change and cumulative absolute change (Table 3). Despite the small difference, both long-term absolute and cumulative absolute change suggests that there was a net loss in urban vegetation over the study period.

To get a sense of the overall scale of change across the Greater Melbourne area, the changes in vegetation recorded in six LGAs were extrapolated to the remaining 26 LGAs using both a conservative and a standard scenario. The standard scenario extrapolated the absolute change over all six LGAs over the 15-year period to the remaining 26 LGAs. In contrast, the conservative scenario extrapolated changes based on the changes in five LGAs, and excluded data from Hume where the absolute change was exceptionally higher in comparison to the other LGAs (see Table 3). The standard scenario suggests that 341.1 square kilometres of urban vegetation are likely to have been lost between 2001 and 2016, whereas in the conservative scenario, 107.8 square kilometres of urban vegetation are likely to have been lost. On an annual basis, this equates to 22.7 square kilometers per year (standard scenario) or 7.19 square kilometers per year (conservative scenario). These rates are similar to those reported for the cities of La Serena, Santiago and Concepcion in Chile, over a similar 20-year time period [69], but were lower than those reported for Kolkata, India [70].

A previous study looking at net vegetation change in Melbourne between 2014–2018 found no net change over this time period [37], whereas in our study we found that there was a change in vegetation over the 2011–2016 time period. Further work would be required to investigate these differences to determine if they can be best explained by the differences in time periods examined, or the different methods and spatial resolution of the datasets used by the two studies.

4.4. Partially Vegetated Category and Dynamic Change Approach

To the best of our knowledge, this is the first study to include the category of partially vegetated in a classification of urban vegetation. The inclusion of this category allowed us to distinguish between absolute change, where we were confident there had been a gain or loss of green because the pixel had changed from vegetated to non-vegetated or vice versa; compared to potential change, where some of the change may be due to factors such as variation in NDVI due to higher or lower rainfall; or uncertainty in the classification due to the difficulties of setting threshold NDVI values that work consistently across time and space. We also offer an example of how differences in NDVI can be accounted for by customising the threshold values for classification when working in cities that have a steep rainfall gradient and diverse bioregions, such as those found in the Greater Melbourne area.

Dynamic change, used in this study, has allowed us to identify a broader spectrum of change in the landscape, which would have been obscured if the traditional net change approach have been used. It also highlighted the importance of the time scale in the detectability of the cumulative loss of vegetation cover. The change detected over five-year intervals was quite variable and influenced by rainfall conditions. However, the change over the full 15-year interval was substantial and more reflective of how effective past policies have been in protecting and enhancing urban greenspaces.

5. Summary, Conclusions and Recommendation

In summary, this study confirms the value of the dynamic change approach proposed by Wang et al. [30] in providing a more complete understanding of both the gain and loss of urban vegetation. It has also confirmed the importance of time scales in the ability to detect longer-term changes in vegetation cover, as the patterns detected at five-year intervals were far more variable than those detected across the full 15 years. This highlights the importance of using longer time intervals to produce a more accurate picture of the trajectory of vegetation cover change in urban landscapes.

Greater Melbourne has possibly lost over 300 square kilometers in urban vegetation cover across the 32 LGAs between 2001 and 2016. This is more than 100 times the size of Central Park in New York City; and equates to a loss of 21.85 square kilometers annually. The ongoing loss of vegetation cover, even in LGAs with policies in place to minimize potential losses, presents a substantial challenge in the context of current efforts to achieve the vegetation and canopy targets that are currently being set for cities around the world. Considerable attention will need to be paid to the policies and resources directed towards these efforts if we are to achieve these targets and maintain the benefits of urban green spaces for the people and biodiversity in our cities now and in the future.

Supplementary Materials: The following are available online at https://www.mdpi.com/article/10.3390/land10080814/s1, Table S1: Summarised data for the pixel count and Area (ha) for each land cover class at each time period, at the municipal scale (entire LGA), Table S2: Summarised data for the pixel count and Area (ha) for each land cover class at each time period, at the scale of 2002 Public Open Space features within four LGAs, Table S3: Absolute dynamic change for each land cover class between the different time periods, summarised at the municipal scale (entire LGA), Table S4: Absolute dynamic change for each land cover class between the different time periods, summarised at the scale of 2002 Public Open Space features within four LGAs, Table S5: Potential and total dynamic change for each land cover class between the different time periods, summarised at the municipal scale (entire LGA), Table S6: Potential and total dynamic change for each land cover class between the different time periods, summarised at the scale of 2002 Public Open Space features within four LGAs.

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